The Chemical Evolution of Galaxies at High Redshift

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Abstract. Observations of absorption lines in the spectra of distant QSOs offer a new approach for tracking the evolution of normal galaxies from early epochs to the present day. The damped Lyα systems are particularly suitable for measuring the properties of what are likely to be the progenitors of present-day luminous galaxies. We have recently concluded a long-term survey of 30 damped absorbers (including eight from the literature) aimed at measuring the metallicity and dust content of the universe from redshift $z = 3.39$ to 0.69. The major conclusions are that the epoch of chemical enrichment in galaxies may have begun at $z \simeq 2.5 - 3$—corresponding to a look-back time of ~ 14 Gyr ($H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $q_0 = 0.01$)—and that at $z \simeq 2$ the typical metallicity was 1/15 of solar. There is clear evidence for the presence of interstellar dust at $z \approx 2$, although several high-redshift galaxies, particularly the most metal-poor, appear to be essentially dust-free. We discuss the nature of the damped Lyα galaxies in the light of these and other new results.

1. Introduction

Our current knowledge of galactic chemical evolution is limited to studies of old Galactic stars and extragalactic H II regions. To probe the chemical evolutionary history of galaxies in general we need to identify normal galaxies and measure element abundances over a large range of redshifts. The so-called 'damped Lyα systems', a class of QSO absorbers with neutral hydrogen column densities $N(\mathrm{H\,I}) > 2\times10^{20}$ cm^{-2}, are ideal targets for this purpose. First, they are selected simply by their strong damped Lyα profiles in the spectra of background QSOs. Studies of damped Lyα systems (see Wolfe 1995 for a recent review) suggest that they are the progenitors of present-day luminous galaxies and that they trace the bulk of neutral material available for star formation at high redshifts. Second, the large neutral hydrogen column density ensures that ionization corrections

are negligible in the calculation of element abundances (Viegas 1995). The typical spectrum of a damped Lyα galaxy is similar to that produced by local interstellar gas seen in absorption against a background star. Indeed, ultraviolet observations of interstellar gas have shown that with a careful choice of elements and transitions, it is possible to determine not only accurate metallicities but also the amount of dust present.

The Zn II doublet at 2025 and 2062 Å is a highly suitable tracer of the degree of metal enrichment for two reasons. In Galactic stars the abundance of Zn tracks those of Fe-peak elements down to very low metallicities (Sneden, Gratton, & Crocker 1991), and in the diffuse interstellar medium Zn is within ≈ 0.2 dex of solar (Sembach et al. 1995; Roth & Blades 1995). An indication of the amount of dust present can be obtained from transitions of Cr II occurring close to the Zn II lines at 2055, 2061 and 2065 Å since in the local interstellar medium $\approx 99\%$ of Cr is depleted onto grains. Moreover, the solar abundances of both Zn and Cr are low, ensuring that the absorption lines are generally unsaturated and the corresponding column densities can be determined relatively accurately. Thus the observation of the small wavelength interval 2025–2065 Å in the rest-frame of a damped Lyα galaxy provides the abundance of iron-peak elements in the interstellar gas via the $N(\mathrm{Zn}^+)/N(\mathrm{H}^0)$ column density ratio, and an indication of the amount of dust present from the $N(\mathrm{Cr}^+)/N(\mathrm{Zn}^+)$ ratio.

2. Observations

Over the last six years we have obtained intermediate dispersion spectra of a large sample of QSOs with damped Lyα systems using the 4.2 m William Herschel Telescope and the 3.9 m Anglo-Australian Telescope. Our first survey paper (Pettini et al. 1994) presented measurements for 15 damped systems; recently we have extended the sample with observations of seven additional systems, mostly at $z > 2.5$. Together with data from the literature (Meyer, Welty & York 1989; Meyer & York 1992; Lu et al. 1995; Meyer, Lanzetta & Wolfe 1995; Steidel et al. 1995a; Smette et al. 1995; Prochaska & Wolfe 1996), the total data set now includes 30 damped Lyα systems over the redshift range $z = 0.69$–3.39, more than one third of the total number known (Wolfe et al. 1996). Zn II absorption has been detected in 14 cases, all but one at $z < 2.5$, and useful upper limits have been obtained for the remaining 16 sightlines. Figure 1 shows all the available data on the abundance of Zn in damped Lyα systems as a function of redshift.

3. Chemical Enrichment in the Early Universe

As can be seen from Fig. 1, the Zn abundances are generally well below solar, indicating that most damped Lyα galaxies are chemically young. At $z \approx 2$—where most data are available—we find an average $\langle[\mathrm{Zn/H}]\rangle = -1.2$ (1/15 solar)[1]. Since at this redshift the damped systems dominate the mass density of

[1]This value is obtained by using the Zn II doublet f-values measured by Bergeson & Lawler (1993) and the solar abundance of Zn from the compilation by Anders & Grevesse (1989). For

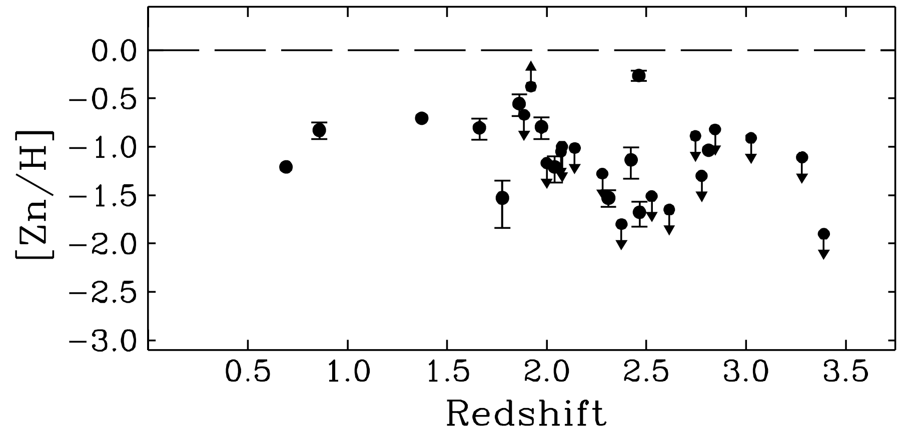

Figure 1. The abundances of Zn relative to solar (on a log scale) in the 30 damped Lyα galaxies in our survey plotted against redshift. Upper limits, corresponding to the non-detection of the Zn II lines, are indicated by smaller dots and downward pointing arrows. The dashed line corresponds to the solar abundance of Zn.

neutral gas in the universe, this average metallicity can be interpreted as the characteristic metallicity of the universe at a look-back time of ≈ 13 Gyr.

Figure 1 also shows that there is a considerable range in the Zn abundance at $z \approx 2$. We know that the full range spans more than 2 orders of magnitude because in several cases where only upper limits are available for Zn, high resolution spectroscopy of other ions with intrinsically stronger lines has shown that the metallicities are very low. For example, Pettini & Hunstead (1990) measured abundances as low as $\sim 1/350$ solar in the $z_{\rm abs} = 2.076$ system towards Q2206−199 ([Zn/H] < -1.0); similarly in the $z_{\rm abs} = 2.279$ system towards Q2348−147, where [Zn/H] < -1.3, Pettini, Lipman & Hunstead (1995) find the abundances of Si, S and Fe to be $\approx 1/100$ of solar. Evidently chemical enrichment did not proceed at the same rate in different galaxies, presumably reflecting the protracted epoch of disk formation (Kauffmann 1996).

The picture at $z > 2.5$ and $z < 1.5$ is more sketchy than between these redshifts, reflecting the observational difficulties in detecting the Zn II absorption lines in the near-infrared and ultraviolet respectively. Nevertheless, the available data do allow some tentative conclusions to be reached. In all but one case Zn is *un*detected at $z > 2.5$ and its abundance is generally lower than -1.2. On the other hand, at $z \simeq 2 - 2.5$, some galaxies had apparently already reached [Zn/H]≥ -0.5. This suggests that the first major episodes of metal production in galaxies probably occurred between $z \simeq 3$ and 2, and that in some cases this process may have proceeded rapidly, on a timescale of 1–2 Gyr. This conclusion

comparison, in Pettini et al. (1994) we deduced $\langle$[Zn/H]$\rangle = -1.0$ (1/10 solar) based on earlier estimates of the f-values and of [Zn/H]$_\odot$.

is consistent with the recent discovery of a significant population of star-forming galaxies at $z \simeq 3$ by Steidel et al. (1995b, 1996).

It is perhaps surprising that no damped Lyα systems with near-solar metallicity have been found at $z < 1$, as we approach the epoch when the Sun formed (at $z \simeq 0.32$ in this cosmology). This may be simply due to the very small number of measurements available (see Fig. 1). The few damped systems imaged to date have all been found to be relatively underluminous galaxies (Steidel et al. 1994, 1995a). It is also possible that at these epochs, when a significant fraction of the gas in galaxies had been cycled through stars and the typical content of heavy elements and dust had risen to values greater than $\sim 1/15$ of those found today, our spectroscopy technique becomes significantly biased *against* the galaxies we are trying to detect. Existing compilations of QSOs with damped Lyα systems are all drawn from magnitude limited optical surveys; interstellar dust may well result in sightlines through chemically unevolved, and therefore relatively unreddened, galaxies being over-represented (Pei & Fall 1995). While this selection effect must be operating at some level, it remains to be established with future observations how important it really is in biasing our view of the universe.

In their study of the chemical evolution of the Galactic disk, Edvardsson et al. (1993) concluded that the age-metallicity relation is relatively flat and shows a large scatter at all ages. If, furthermore, disk formation in the universe was not a coeval process but, as seems more likely, took place over a protracted epoch (Kauffmann 1996), we would not expect a tight trend in plots such as that shown in Fig. 1. Nevertheless, even the broad characteristics of the chemical history of damped Lyα galaxies appear to be significantly different from those of the disk of the Milky Way. In particular, the distribution of metallicities at $z \simeq 2$ resembles more closely that of stars in the halo, rather than the thick or thin disk (see for example Fig. 16 of Wyse & Gilmore 1995). On the basis of the chemical evidence we would conclude that at $z \simeq 2$ most galaxies had not yet collapsed to form disks and that the damped Lyα systems trace an earlier stage in the formation of galaxies, possibly to be identified with the spheroidal component. It will be very interesting to assess whether other lines of evidence, particularly the kinematics and the morphology of high redshift galaxies (now accessible with the Hubble Space Telescope), support this conclusion or not.

4. Dust in Young Galaxies

Turning now to Cr, we find that this element is generally less abundant than Zn by factors of up to > 5. This may reflect an intrinsic departure from solar relative abundances, but such an effect is seen only in the most metal-poor stars in our Galaxy, with [Fe/H] < -2.5 (McWilliam et al. 1995). By analogy with the local interstellar medium, we consider it more likely that a fraction of the gaseous Cr has been incorporated in dust grains. Typically, we find that about half of the Cr is 'missing' from the gas phase. If this also applies to other grain constituents, then the dust-to-gas ratio at the typical metallicity of 1/15 solar is $\approx 1/30$ of that of the Milky Way. This low value is consistent with the mild reddening found towards background quasars with damped Lyα systems in their spectra (Pei, Fall & Bechtold 1991). If we compare our Cr/Zn ratios with those

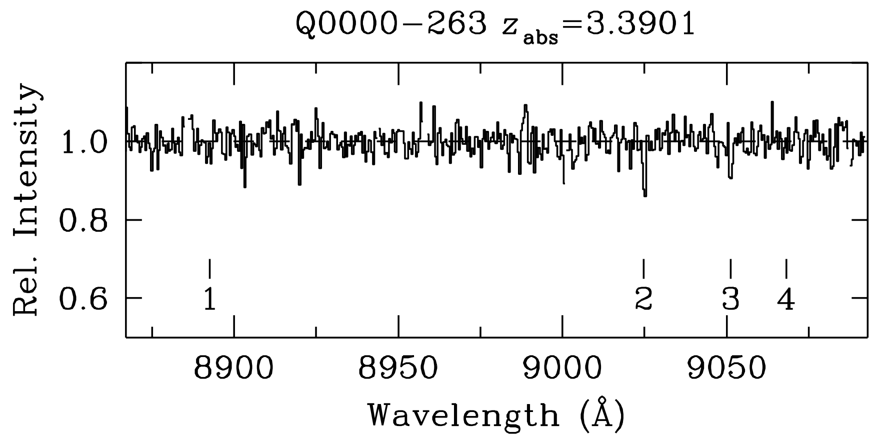

Figure 2. Portion of the AAT spectrum of Q 0000−263 showing Cr II absorption in the damped Lyα system at $z = 3.3901$. The vertical tick marks indicate the expected locations of absorption lines of interest, whether they are detected or not. Line 1: Zn II 2025.5; line 2: Cr II 2055.6; line 3: Cr II 2061.6 + Zn II 2062.0 (blend); and line 4: Cr II 2065.5 . This spectrum has S/N = 30 (note the expanded vertical scale) and FWHM = 1.1 Å.

measured in the local interstellar medium (see Fig. 7 of Pettini et al. 1994), we find that the gas phase abundance of Cr is one order of magnitude higher in the damped systems. This points to significant differences in the physical processes which determine the balance between gas and dust in the interstellar media of these high-redshift galaxies, compared to the Milky Way today.

There is a hint in our survey that the Cr depletion may decrease with decreasing metallicity. Thus, in the lowest metallicity systems ([Zn/H]< -1.7), we may expect to detect preferentially the Cr II lines since Cr is ~ 11 times more abundant than Zn in the Sun.

One such case is shown in Fig. 2. In our high S/N AAT spectrum of Q0000−263, Zn II lines in the damped absorber at the $z = 3.3901$ remain undetected, implying an upper limit to the Zn abundance [Zn/H] ≤ -1.90 ($\leq$ 1/80 solar). However, Cr II absorption is clearly present and we deduce [Cr/H] $= -2.2 \pm 0.1$, or only 1/150 solar. This is similar to the values reported by Molaro et al. (1996) from high resolution spectroscopy of several other ions, suggesting that the interstellar gas in this galaxy is essentially dust-free. Steidel & Hamilton (1992) have imaged the absorber and identified it with a luminous galaxy ($L \approx 3\,L_*$) of dimensions 10–20 h^{-1} kpc. Evidently, here we have an example of a 'normal' galaxy at a very early stage of evolution.

In summary, it is clear that through the damped Lyα absorption systems we have a direct view of the early stages in the evolution of galaxies. A substantial body of data is now being obtained on chemical enrichment, relative abundances of different elements, kinematics, and morphologies—and on how these properties evolve over cosmological timescales. Taken together, these new observations should provide a detailed picture for comparison with current theories of galaxy

formation.

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References

Anders, M.V. & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197

Bergeson, S.D. & Lawler, J.E. 1993, ApJ, 408, 382

Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D.L., Nissen, P.E. & Tomkin, J. 1993, A&A, 275, 101

Kauffmann, G. 1996, MNRAS, in press

Lu, L., Savage, B.D., Tripp, T.M. & Meyer, D.M. 1995, ApJ, 447, 597

McWilliam, A., Preston, G.W., Sneden, C. & Searle, L. 1995, AJ, 109, 2757

Meyer, D.M., Lanzetta, K.M. & Wolfe, A.M. 1995, ApJ, 451, L13

Meyer, D.M., Welty, D.E. & York, D.G. 1989, ApJ, 343, L37

Meyer, D.M. & York, D.G. 1992, ApJ, 399, L121

Molaro, P., D'Odorico, S., Fontana, A., Savaglio, S. & Vladilo, G. 1996, A&A, in press

Pei, Y.C. & Fall, S.M. 1995, ApJ, 454, 69

Pei, Y.C., Fall, S.M. & Bechtold, J. 1991, ApJ, 378, 6

Pettini, M. & Hunstead, R.W. 1990, Australian J. Phys., 43, 227

Pettini, M., Lipman, K. & Hunstead, R.W. 1995, ApJ, 451, 100

Pettini, M., Smith, L.J., Hunstead, R.W. & King, D.L. 1994, ApJ, 426, 79

Prochaska, J.X. & Wolfe, A.M. 1996, ApJ, in press

Roth, K.C. & Blades, J.C. 1995, ApJ, 445, L95

Sembach, K.R., Steidel, C.C., Meyer, D.M. & Macke, R.J. 1995, ApJ, 445, L27

Smette, A., Robertson, J.G., Shaver, P.A., Reimers, D., Wisotzki, L. & Kohler, T. 1995, A&A, 303, 968

Sneden, C., Gratton, R.G. & Crocker D.A. 1991, A&A, 246, 354

Steidel, C.C., Bowen, D.V., Blades, J.C. & Dickinson, M. 1995a, ApJ, 440, L45

Steidel, C.C., Giavalisco, M., Pettini, M., Dickinson, M. & Adelburger, K.L. 1996, ApJ, in press

Steidel, C.C. & Hamilton, D. 1992, AJ, 104, 941

Steidel, C.C., Pettini, M., Dickinson, M. & Persson, S.E. 1994, AJ, 108, 2046

Steidel, C.C., Pettini, M. & Hamilton, D. 1995b, AJ, 110, 2519

Viegas, S.M. 1995, MNRAS, 276, 268

Wolfe, A.M. 1995, in QSO Absorption Lines, G. Meylan, Berlin: Springer, 13

Wolfe, A.M, Lanzetta, K.M., Foltz, C.B. & Chaffee, F.H. 1996, ApJS, in press

Wyse, R.F.G. & Gilmore, G. 1995, AJ, 110, 2771